JAMES B. FRIAUF

ELECTROMAGNETIC SHIP PROPULSION

THE AUTHOR

is an electrical engineer with the Electrical Branch of the Bureau of Ships. He studied at several universities and has a Ph.D. degree in physics and mathematics from the California Institute of Technology. Since 1940, he has been with the Department of Defense, with the Bureau of Ordnance for about a year, and with the Electrical Branch of the Bureau of Ships ever since. He is a civil member of the American Society of Naval Engineers, and a fellow of the American Physical Society and the American Association for the Advancement of Science.

ELECTROMAGNETIC SHIP PROPULSION, also known as magnetohydrodynamic propulsion, has recently been attracting attention of a number of inventors. It is an intriguing scheme with a number of readily apparent advantages. Among these are: (a) silence, a feature of considerable interest for submarines; (b) simplicity of structure and absence of moving parts; and (c) proven workability of the same principle in electromagnetic pumps for liquid metals [1, 2, 3, 4, 5].

But these qualitative and readily apparent advantages are accompanied by quantitative disadvantages which are not so immediately apparent. It is the purpose of this article to give a fundamental relationship relevant to electromagnetic ship propulsion and electromagnetic pumps; to check this against experimental results reported for electromagnetic pumps; and then use it to arrive at conclusions as to the feasibility of electromagnetic ship propulsion.

THE STRUCTURE CONSIDERED

The essential parts of the electromagnetic ship propulsion arrangement considered are indicated in Figure 1 and are:

1. A horizontal water channel open at both ends extending longitudinally through the ship.
2. A magnet or other means for producing a magnetic field throughout the water channel.
3. Electrodes at each side of the channel and a source of power to send a direct current through the channel at right angles to the magnetic flux.

The arrangement described is a simple d-c motor in which the sea water in the channel is the current conductor in what corresponds to the armature circuit of a conventional d-c motor. The force caused by the action of the magnetic field on the current will push the water backward with respect to the channel (see Figure 1). We can look upon the arrangement as a jet propulsion scheme in which a sea water electromagnetic pump is used to produce

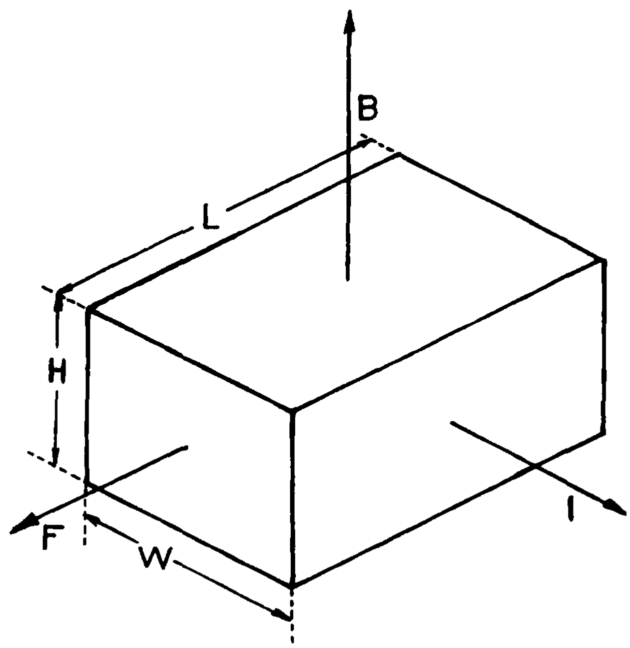

Figure 1.

the jet. The type of pump described is one which has been used for pumping liquid metals and is known as the direct-current Faraday type or the direct-current conduction type.

In order to arrive at a quantitative relationship, it will be assumed that the sea water in the channel acts like a rigid body in the conversion from electrical to mechanical power which is effected by the action of the crossed magnetic field and current; that the magnetic flux density, the current density, and the water velocity are constant in magnitude and direction at all points in the water channel and are everywhere mutually perpendicular; that there are no losses caused by "fringing" of the magnetic field or current at the ends of the channel; that the magnetic field is given to us free of any charge for power to produce the field; and that the propulsion efficiency is equal to the pump efficiency.

It should be noted that the assumptions have been made in such a way as to give a favorable rather than an unfavorable estimate of the capabilities of electromagnetic ship propulsion. This is because our primary purpose is to arrive at a reliable estimate of the maximum possible performance that can be expected from electromagnetic ship propulsion under the most favorable conditions. If this turns out to be so low as to cast a shadow on its practicability, a closer estimate is not needed.

DERIVATION OF A FUNDAMENTAL RELATIONSHIP

We shall assume that the water channel is of rectangular cross section with dimensions as indicated on Figure 1. The back electromotive force (bemf) generated by motion of the water through the magnetic field is:

$$\text{bemf} = BWV \times 10^{-8} \text{ volts} \quad (1)$$

where B is the magnetic flux density in gausses, W is the width of the channel in centimeters, and V is the water velocity in centimeters per second.

The resistance of the water in the channel in the direction of the current is:

$$R = \frac{rW}{HL} \text{ ohms} \quad (2)$$

where r is the specific electrical resistance of the fluid in the channel in ohm centimeters, and W, H and L are channel dimensions in centimeters.

If E is the voltage applied to the electrodes at opposite sides of the water channel, the current through the water in the channel is:

$$I = \frac{E - \text{bemf}}{R} = \frac{(E - BWV \times 10^{-8})HL}{rW} \text{ amperes} \quad (3)$$

The force exerted on the water in the channel is:

$$F = BWI \times 10^{-1} = \frac{BW(E - BWV \times 10^{-8})HL \times 10^{-1}}{rW} \text{ dynes} \quad (4)$$

The mechanical power imparted to the water in the channel is:

$$P_i = FV \times 10^{-7} = \frac{BV(E - BWV \times 10^{-8})HL \times 10^{-8}}{r} \text{ watts} \quad (5)$$

The electric power input needed to do this is:

$$P_e = EI = \frac{E(E - BWV \times 10^{-8})HL}{rW} \text{ watts} \quad (6)$$

The efficiency is:

$$e = \frac{P_i}{P_e} = \frac{BWV \times 10^{-8}}{E} \quad (7)$$

The efficiency as so defined will henceforth be referred to as the electrical efficiency. It is the efficiency of the electromagnetic conversion from electrical to mechanical power in the sea water channel, that is, the mechanical power put into the water divided by the electric power input needed to produce the mechanical power. The electrical efficiency takes no account of the hydraulic losses in the water, which will reduce the useful power output of the pump, and also takes no account of whatever power may be needed to maintain the magnetic field. The electrical efficiency is thus an upper limit to the overall efficiency of the pump and of electromagnetic ship propulsion, not the overall efficiency itself.

From equation (7) it is apparent that:

$$\frac{1-e}{e} = \frac{E - BWV \times 10^{-8}}{BWV \times 10^{-8}} \quad (8)$$

and that:

$$E-BWV\times10^{-8}=BWV\times10^{-8}\left(\frac{1-e}{e}\right)\text{volts}\ldots\ldots(9)$$

Substituting this value for $E-BWV\times10^{-8}$ in equation (5) gives:

$$P_i=\frac{B^2V^2\times10^{-16}\times(1-e)HLW}{re}\text{watts}\ldots\ldots\ldots(10)$$

or:

$$S_i=\frac{P_i}{HLW}=10^{-16}\left(\frac{B^2V^2}{r}\right)\left(\frac{1-e}{e}\right)\text{watts cm}^{-3}\ldots.(11)$$

It is convenient to introduce some English units before using equation (11). When this is done it becomes:

$$s_i=2.64\times10^{-12}\left(\frac{B^2v^2}{r}\right)\left(\frac{1-e}{e}\right)\text{kw ft}^{-3}\ldots\ldots..(12)$$

where s_i = specific mechanical power input to the water in kw ft^{-3}
v = water velocity in ft sec^{-1}
B, r, and e are in the same units as before.

COMPARISON WITH LIQUID METAL PUMP

Equation (12) is valid for liquid metal pumps as well as for sea water pumps. It is, therefore, of interest to compare its predictions with the following data given by Jaross and Barnes [2] for a liquid sodium pump:

Pumping channel size:	6″ in direction of magnetic flux 20.875″ in direction of current 30″ in direction of fluid flow
Current:	250,000 amperes
Discharge:	10,000 gpm
Pressure head:	25 psi
Magnetic flux density:	4,000 gausses
Efficiency:	0.20 (approximately)

From the data tabulated above, we can readily calculate the following additional information:

Fluid velocity	25.6 ft sec^{-1}
Volume of pumping channel	2.18 ft^3
Useful power output (10,000 gpm at 25 psi):	109 kw
Specific mechanical power output:	50.0 kw ft^{-3}

Now substitute into equation (12), B=4,000 gausses, v=25.6 feet per second, and $r=20\times10^{-6}$ ohm cm, the specific resistance of liquid sodium at the temperature at which it was used. The result is:

$$s_i=1383(1-e)/e\ldots\ldots\ldots\ldots.(13)$$

We do not yet know the electrical efficiency, e, but it seems reasonable to suppose that the overall efficiency, 0.20 is equal to e x e* where e* is an efficiency that takes into account the hydraulic friction loss and all other losses. Furthermore, the specific power output is 50.0 kw per cubic foot. Making use of these two pieces of information gives e=0.865 and e*=0.231. Substituting this value of e in equation (13) gives s_i=216 kw per cubic foot. While this comparison with experimental results can hardly be considered a complete verification of equation (12), it furnishes ample experimental support for one of the predictions from this equation, namely, that the specific power input to the fluid can be very high even for high electrical efficiency if the fluid being pumped has a specific resistance as low as that of liquid sodium.

APPLICATION TO SEA WATER PUMPS

The situation is altogether different for sea water pumps. When we substitute into equation (12), r=20 ohm cm, the specific resistance of sea water the result is:

$$s_i=1.32\times10^{-13}B^2v^2(1-e)/e\ldots\ldots\ldots(14)$$

Computed values of s_i for different values of B, v, and e are given in Table I, in which the unit for the Bv product is gauss ft sec^{-1}.

TABLE I

e	$Bv=10^3$	$Bv=10^4$	$Bv=10^5$	$Bv=10^6$
0.99	1.33×10^{-9}	1.33×10^{-7}	1.46×10^{-4}	1.33×10^{-3}
0.90	1.46×10^{-8}	1.46×10^{-6}	1.19×10^{-3}	1.46×10^{-2}
0.50	1.32×10^{-7}	1.32×10^{-5}	1.31×10^{-1}	1.32×10^{-1}
0.10	1.19×10^{-6}	1.19×10^{-4}	1.33×10^{-5}	1.19
0.01	1.31×10^{-5}	1.31×10^{-3}	1.32×10^{-3}	13.1

It is immediately apparent from Table I that for a sea water pump reasonably high electrical efficiency is accompanied by intolerably low specific power input to the water in the pumping channel, and that high specific power input is accompanied by intolerably low electrical efficiency. This highly undesirable combination of characteristics seriously limits the performance of electromagnetic ship propulsion. To see this it is instructive to make a few estimates for pumps such as might be used for ship propulsion. The starting parameters chosen are:

Mechanical power input to the water=1,000 kw. This is very small for a propulsion installation, particularly since only a part of this input will be available for propulsion because of hydraulic losses. Even so, the water channel turns out to be huge.

Magnetic flux density=5,000 gausses. This is more than the flux density in the liquid sodium pump described by Jaross and Barnes and is considerably higher than is practical for the large volume needed for a sea water pump. It will be used, however, in view of our objective of estimating the maximum possible performance of electromagnetic ship propulsion under the most favorable conditions.

Electrical efficiency, e=0.15. This is a low efficiency but the volume of the water channel is large. It would be even larger for a higher efficiency.

Cross section of channel. Calculations for the pumps of Table II are based on a pumping channel which is square in cross section, W feet on a side.

TABLE II

Calculated performance of d-c Faraday type electromagnetic pumps for sea water

For both pumps

Mechanical power input to water, P_1, kw	1,000	
Velocity of water, v, ft sec^{-1}	40	
Force exerted electromagnetically on water, F, pounds	18,430	
Magnetic flux density, B, gausses	5,000	
Electrical efficiency, e	0.15	
Water channel volume, W^2L, ft^3	33,400	
	Pump I	*Pump II*
W, ft	28.8	38.4
L, ft	40.2	22.7
I, amperes	18,660	14,020
IR, volts	304	405
E, volts	357.6	476.4
$EI \times 10^{-3}$, electric power input, kw	6,660	6,660
Hydraulic efficiency	0.20	0.40
Useful power output, kw	200	400
Overall efficiency	0.03	0.06

Both pumps illustrate the disadvantages of electromagnetic ship propulsion, enormous volume even for small power output, and low efficiency. Nor, as can be seen from equation (12), can anything be done about it unless the B^2v^2/r factor can be substantially increased. There are only three ways to increase this factor, increase B, increase v, or decrease r.

The magnetic flux density of 5,000 gausses assumed for Table II is already well above what would be feasible for the large water volume needed. To produce the magnetic field assumed for Table II by means of permanent magnet material would require more than 30,000 tons of Alnico V, one of the high performance permanent magnet materials with a maximum energy product of 5×16^6 gauss oersteds. Nor, although detailed calculations have not been made on this point, does it seem likely that too much would be gained by going to field coils since these would require not only a considerable weight of copper and soft iron for the coils and magnetic structure but a continuous expenditure of fuel to produce the power needed to energize the coils. Unless there is some unforeseen breakthrough which makes it possible to produce very large magnetic fields over large volumes of sea water, it does not appear that electromagnetic ship propulsion can be made practical by increasing B.

Increasing v would be as effective as increasing B, but the hydraulic losses mount up fast as v is increased and limit what can be done in this way. A study of this problem indicates that either the magnetic flux density or the channel cross section must be increased as v is increased if neither the hydraulic nor the electrical efficiency is to decrease. It appears, therefore, that an increase in v would necessarily lead also to an increase in B or W, both of which would be undesirable.

The sole remaining alternative is to decrease r, the specific resistance of sea water. It has been suggested by some of the proponents of electromagnetic ship propulsion that r be decreased by injecting into the water channel some ingredient that would decrease the resistivity of sea water. Unfortunately, these suggestions have not been accompanied by any instructions on how to make the necessary ingredient. If we knew how, electromagnetic ship propulsion might begin to look attractive.

As things are, it does not look attractive. It illustrates once again the well known proposition that a high efficiency electric motor of reasonable size simply cannot be built by using a conductor of high resistivity. And sea water is of very high resistivity indeed when one is talking in terms of conductors. Its resistivity is about one million times that of the liquid sodium that is being pumped in some of the electromagnetic liquid metal pumps. A factor of a million is enough to make the difference between a pauper and a millionaire. It is not surprising that such a factor will make a corresponding difference in electromagnetic pumps.

CONCLUSIONS

The purpose of this study has been to estimate an upper limit to the performance of electromagnetic ship propulsion on the basis of highly favorable assumptions. The conclusions reached are that:

(1) This limit is so low that electromagnetic ship propulsion is highly unattractive. The resistivity of sea water being what it is, practically realizable values of B and v give values of B^2v^2/r so small that electromagnetic ship propulsion will be bulky and inefficient.

(2) The only ways to remedy this situation are to decrease r, increase B, or increase v. Nothing now visible on the horizon indicates that any one or any combination of these factors can be changed enough to make electromagnetic ship propulsion look attractive. Of course there may at some time be a breakthrough which will change the picture. Until then, the prospects for electromagnetic ship propulsion look bleak.

REFERENCES

[1] J. F. Cage, Jr., "Electromagnetic Pumps for High-Temperature Liquid Metal." *Mechanical Engineering,* 75, 467-471 (June 1953).

[2] R. A. Jaross and A. H. Barnes, "Design and Operation of a 10,000-gpm d-c Electromagnetic Sodium Pump and 250,000-ampere Homopolar Generator." Proceedings of the Second United Nations Conference on the Peaceful Uses of Atomic Energy Held in Geneva 1 Sept.-13 Sept., 1958. Volume 7, pages 82-87.

[3] L. R. Blake, "Conduction and Induction Pumps for Liquid Metals." The Proceedings of the Institution of Electrical Engineers, *104,* Part A, 49-63. Discussion 63-67 (February 1957).

[4] A. H. Barnes and J. F. Cage, Jr., "Pumps—Electromagnetic." Liquid Metals Handbook, Sodium—NaK Supplement, 1 July 1955, pages 288-305.

[5] W. B. Woollen, "Electromagnetic Pumps for Reactors." *Nuclear Power,* 2, 267-276 (July 1957).